Research article

Techno-economic assessment of microgrid in rural India considering incremental load growth over years

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Abstract: India, being a developing country with a fast-growing economy, experiences ever increasing electrical energy demand. Industrial and economic development in rural India is impeded by inadequate, erratic and unreliable grid supply. This has resulted in underperformance of small-scale manufacturing and service industries. Dependency on fossil fuel-based sources as an alternative increases the operation costs and carbon emissions. Migration to cleaner energy ensures sustainable solution and addresses the issues of depleting fossil fuels, global warming and environmental hazards. In this regard, hybrid renewable energy systems have gained wide acceptance as optimum solution. Hence, authors have optimally designed hybrid energy system for power deprived rural Indian villages. Authors have heeded to the vital element of incremental load growth over years while designing the microgrid to sustain the increasing load demand of emerging economy of developing country. HOMER Pro Software is utilized to accomplish system size optimization and authors have gained comprehensive insights into techno-financial feasibility for different dispatch strategies of the proposed energy system. The levelized cost of electricity of the optimal off-grid system catering to multiyear incremental load growth is 0.14$/kWh indicating that proposed system is promising in terms of commercial efficacy. The study performs a detailed analysis of the results obtained during different phases of the project to ensure robustness and supply continuity of the proposed system. The paper also includes comparison of the carbon footprint in the proposed system with that of existing system.

1. Introduction

Paris Agreement was accepted by 197 countries to combat climate change by reducing greenhouse gases [1]. World is looking forward to renewable energy with minimal carbon footprint as sustainable substitute to fossil fuels for electricity generation. India has planned to adopt cleaner energy for catering to the ever-increasing electricity demand by expanding the overall renewable capacity from 32 GW (in 2014) to 175 GW (in 2022) [2]. Renewable energy (RE) capacity additions are on constant rise owing to the reduced tariffs of solar power. The integration of RE/distributed sources in power system has led to the evolution of Hybrid Renewable Energy System (HRES), also known as Microgrid. Microgrids are state-of-art, active distribution networks comprising of distributed generation, energy storage systems (ESS) and loads, which are operated in islanded or grid-connected mode in a controlled way.

Basic driving factors behind microgrid development and deployment can be broadly classified into three categories namely energy security, economic benefits and clean energy integration. Energy security deals with severe weather conditions, cascading outages and cyber and physical attacks as decentralized architecture are less vulnerable to attacks. Further, economic benefits concern infrastructure cost savings like those of transformer and long transmission lines; fuel savings by reduced line losses and combined heating cooling and power; and ancillary services with intentionally islanded operation. Clean energy integration which addresses the challenges like voltage control, steep ramping, over generation etc of variable and uncontrollable resources like PV and wind. Besides attaining above mentioned purposes, resiliency and emissions should be prioritized and this has led to extensive research in microgrids design. The primary driver of microgrid design and development is its capability to improve the resiliency and reliability and serve critical facilities like health care, communications, and emergency response infrastructure. Further, aging infrastructure and cascading outages events drive microgrids development to serve whole communities [3]. To this end, resiliency should be quantified for microgrid systems based on certain set of factors [4], and the microgrid architecture should be structured into functional layers to integrate the hardware and software equipment to attain heterogeneous automation and appropriate monitoring systems [5]. Further, the resilience strategies preferred by different types of microgrids, different energy management systems, microgrids' individual components resilience and communication resilience should be analysed as well [6]. Thus, proper planning of microgrid design and operation becomes mandatory for attaining goals of sustainability and resiliency.

The villages in India currently receive single-phase power supply from the grid, characterised by frequent and unplanned power cuts that makes it unreliable and inadequate. The increase in economic activity in terms of manufacturing, increasing population and development strains the system, which is already suffering of insufficient power supply. This enforces the dependency on fossil fuel-based energy sources viz. diesel generator, which escalates the cost and carbon footprint significantly. Rural India has abundance of renewable energy sources, hence renewable sources can become one stop sustainable solution to the above-mentioned issues. The economic activities are

migrating to rural areas for financial viability, and this necessitates the service to rural areas with a larger quantum of energy beyond basic household lighting. An off-grid system of renewable energy can serve as a scalable, appropriate and viable solution for supplying power to un-electrified or power deficient hamlets. Standalone systems have attracted the focus of power system designers as a reliable solution, in view of the limitations that exist towards expansion of electric power grid owing to low fossil fuel reserves and environmental issues. Further high quality, reliable and customized electricity service in off-grid systems helps improve customer satisfaction. A proper energy planning which takes the supply, and a realistic evaluation of increasing demand is essential to fulfil the ever-increasing energy needs. Therefore, authors have considered off-grid microgrid design as a dependable solution considering multiyear load growth. Outputs of RE sources have the inherent issues of being intermittent, stochastic, highly variable and less controllable, due to which, ESS that can mitigate these problems, are utilized in microgrids. However, the cost of microgrids comprising RE sources and ESS can be prohibitively high if not planned appropriately. Therefore, the size and operation of the HRES are optimized for the considered load demand.

Resource optimization plays major role in the assessment of the effectiveness of hybrid renewable energy systems. Researchers are utilizing different methods in planning and sizing the hybrid renewable energy systems. Subhes C Bhattacharyya suggests that the cost of electricity per unit is high for the small off-microgrid system and decreases as the size increases [7]. W Margaret Amutha et al. considered available local renewable energy resources and deduced that the expansion of existing grid lines is not a viable choice from both cost and environment perspectives [8]. In [9] authors have assessed off-grid electrification programs based on mini-grid in developing countries, and they observed that low development and sustainability challenges, lack of proper maintenance and poor energy efficiency utilization measures before the commissioning of the project have led to failure of many projects. Hence, proper planning of microgrid is mandatory to achieve optimum costs and reliable operation, avoiding over-sizing or under-sizing.

Whitefoot et al. compared different dispatch strategies for energy storage planning using HOMER [10]. S.M. Sajed Sadati et al. performed sizing of HRES based on estimated and calculated meteorological data [11]. Tzu-Chieh Hung and Kuei-Yuan Chan proposed a gradual planning of a HRES by optimally designing the microgrid considering resource uncertainty [12]. Makbul AM Ramli, et al. investigated optimal PV, inverter and PV/inverter sizes for a grid-connected PV system by using HOMER [13]. An extensive review on cost optimization, unit sizing and energy management of renewable energy system is done in [14]. A detailed review of Integrated Renewable Energy Source comprising integration configurations, sizing methodologies, storage options and control for management is discussed in [15].

The recent trend of optimization for Hybrid Renewable Energy System (HRES) demonstrates that artificial intelligence serves as the preferred choice for optimization of microgrid operations [16]. Subho Upadhyay developed optimal HRES model by establishing comparative analysis of genetic algorithm, particle swarm optimization, and HOMER software [17]. Technical and economic feasibility of installing hybrid photovoltaic-wind power plant using HOMER software is studied in [18–21]. A comparative analysis of potential configurations of a system best suited to meet the demands of isolated communities through simulation results using HOMER are presented in [22]. Sayedus S et al. utilized unique features of two software tools, HOMER and RET Screen, to perform techno-economic optimization and energy analysis of renewable energy systems [23].

Capacity shortage is always a continuing issue in developing countries. On the other hand, load demand keeps increasing over years. This necessitates a careful expansion planning of microgrid, as it is a potential sustainable solution to capacity shortage problem. Asad W et al. describes expansion planning of off-grid microgrid with controllable loads by considering the uncertainties of load forecasting [24]. Optimal capacity expansion planning of the distributed generation is done to meet the increasing load demand economically [25–27]. Rather than going for capacity expansion at the later stage, proper planning of microgrid considering incremental load growth over years should be done during initial phases.

This research work aims at evaluating the extension of reliable and sustainable power to those deprived of essential energy supply in rural India. The goal is to end energy poverty and transform the livelihoods of the under-served in developing nations. Planning of sustainable and scalable models of microgrid for delivering reliable electricity considering multi-year load growth is undertaken to serve this end, the aim of the research work is to find the optimal, techno-financial, cost-effective hybrid renewable energy system catering to multi-year load growth. This study aims at bridging the following research gaps

- The proposed design considers incremental load growth over years for sizing of the components of microgrid. Available literatures utilize existing load data for microgrid design over project's complete lifetime without any consideration of load growth, and this can be technically and financially misleading especially for rapidly developing nations like India.
- Another key factor that needs consideration while designing the microgrid would be the amount of degradation of energy resources over the years.
- Dispatch strategies ensuring supply continuity and maximum renewable penetration are analysed in detail. Most of the literatures lack this analysis.
- Further, pollutant emissions and carbon footprint of the proposed design and the existing system is determined and compared to substantiate supremacy of the proposed system.

This work considers an off-grid microgrid comprising solar, battery and diesel generators. Li-ion battery leads to significant reduction in specific carbon footprint in the energy sector and increased sustainability [28]. Therefore, authors have employed Li-ion batteries in the work undertaken. We have simulated the microgrid the considering different Energy Management Strategies (EMS) namely Cycle Charging (CC) and Load Following (LF). Economic analysis and detailed technical viability is indispensable part of the framework of designing a sustainable energy system for developing countries. Hence, we have carried out a detailed technical and economic analysis for multiple years of the project lifetime. This simulation considers various benchmark costs of microgrid components as per Central Electricity Regulatory Commission (CERC), Government of India [29].

The paper is organized in following manner. Section 2 deals with modelling of proposed microgrid, assessment of load and resource, and provides insight into the controller employed. Section 3 provides details of various technical and financial parameters used in work undertaken. Section 4 analyses the technical and economical results obtained from the work and compares the proposed system with the existing system and section 5 concludes the paper.

2. Modelling of the proposed microgrid

We have collected primary data of load details from customer surveys of over 10,049 rural households and 2,019 rural enterprises, across four Indian states—Bihar, Uttar Pradesh, Odisha and Rajasthan [30]. Table 1 presents the detail of this consumer behaviour and demand survey. Diesel generators fulfil more than 60% of electricity requirements by the enterprises in these villages [30]. The supply metrics suggests that the average hours of grid-electricity supply per day is worst in Uttar Pradesh, when compared to other three states, with only 11.6 hours of supply. So, a village in Uttar Pradesh, named Kalyanpur Manikpur (India (25°48.0'N, 82°58.1'E)) is considered for the research work. We have simulated a microgrid catering incremental load of the village considering available resources at the physical location.

2.1. Resource assessment

Authors have collected solar data from National Solar Radiation Database from National Renewable Energy Lab Database [31]. Figure 1 shows the Monthly Averages of Solar Radiation (kWh/m^2/day) and Clearness Index of a village at Uttar Pradesh. Scaled annual average of daily radiation in village of Uttar Pradesh is 5.7 kWh/m^2/day, with radiation varying from 4.2 kWh/m^2/day to 6.8 kWh/m^2/day. Clearness Index indicates the fraction of the solar radiation striking the top of the atmosphere that makes it through the atmosphere to strike the Earth's surface.

Table 1. Details of the survey conducted to collect primary load data.

Total No. of rural households surveyed	10,049
Total No. of villages surveyed	200
Total No. of rural enterprises surveyed	2,019
Average population of a village	4,650
Average No. of households in a village	860
Average No. of enterprises in a village	100
Average households using irrigation pumps in a village	300
Residential load demand and peak load	948 kWh/day & 172.2 kW
Commercial load demand and peak load	163 kWh/day &32.19 kW
Agricultural load demand and peak load	750 kWh/day & 205 kW
Average electricity demand of a village and peak load	1,861 kWh/day & 409 kW

Figure 1. Monthly averages of solar radiation (kWh/m^2/Day) and clearness index.

2.2. Village load assessment

Effective load estimation for any area is a primary prerequisite for sizing of Microgrid. Load is estimated based on population of the area, number of houses in that area, number of appliances used and hourly consumption patterns of the appliances as observed in Tables 2 and 3. Numbers of appliances are decided based on consumer behaviour and demand of the population and number of houses in the selected area. The expected hourly consumption patterns of these appliances are decided based on their general use. The baseline electricity demand of a village is 1826 kWh/day where households use 52%, enterprises 7% and agriculture 41% [30]. We have added loads of primary health centre and primary schools to this surveyed load demand, as these loads are coming up in the villages and are the need of the hour. Primary schools and health centre load is considered as commercial load, leading to total demand in village as 1861 kWh/day.

Table 2. Estimated electricity demand of rural households.

| | Rural Household Energy Demand | | | | |
	Appliances	No. of Appliances	Avg. Watt (W)	Avg. Hours of Use	Total Power (W)	Total Energy (Wh)
1.	Ceiling fans	460	70	13	32200	418600
2.	Incandescent bulbs	140	97	8	13580	108640
3.	Table fans	235	60	8	14100	112800
4.	Desert coolers	38	220	9	8360	75240
5.	Led lights	731	8	8	5848	46784
6.	Electric iron	48	851	1	40848	40848
7.	Water pumps	35	1265	1	44275	44275
8.	Television sets	294	36	5	10584	52920
9.	Refrigerator	60	41	19.5	2460	47970
	Maximum peak demand (W) = 172255					
	Total energy consumed by residential load (Wh) = 948077					

Table 3. Estimated electricity demand by commercial activities in the rural area.

	Appliances	No. of Appliances	Avg. Watt(W)	Avg. hours of use	Total power (W)	Total energy (Wh)
Energy demand of rural enterprises						
1.	Flour mills	2	7460	4	14920	59680
2.	Ceiling fans	83	75	6	6225	37350
3.	Table fans	28	72	7	2016	14112
4.	Printer/ photocopier	3	350	4	1050	4200
5.	Refrigerator	10	41	9	410	3690
6.	Led lights	70	8	8	560	4480
7.	Welding Machines	1	1328	4	1328	5312
8.	Incandescent Bulbs	10	103	3	1030	3090
9.	Laptops	4	50	6	200	1200
Energy demand of primary school						
1.	Tube lights	15	35	6	525	3150
2.	Led lights	11	6	6	66	396
3.	Fans	15	75	6	1125	6750
4.	Computers	1	160	5	160	800
5.	Small water pump	1	100	3	100	300
Energy demand of primary health centre						
1.	Tube lights	5	35	8	175	1400
2.	Led lights	25	6	7	150	1050
3.	Fans	10	75	6	750	4500
4.	Exhaust fans	2	30	8	60	480
5.	Halogen lights	1	300	7	300	2100
6.	Mobile phone charging	5	5	8	25	200
7.	Computers	1	160	3	160	480
8.	Printers	1	100	3	100	300
9.	Vaccine refrigerator	1	300	24	300	7200
10.	Small water pumps	1	100	4	100	400
11.	Centrifuge	1	350	1	350	350

Maximum peak demand (W) = 32185
Total energy consumed by commercial load (Wh) = 162970

Authors have estimated the demand for different categories naming residential loads, commercial loads and agriculture loads. Table 2 gives the estimated electricity demand of rural households of the village. In villages, electricity demanded for domestic purpose is for appliances like compact fluorescent lamps, fans, TV, fridge, water pumping etc. Table 3 gives the estimated electricity demand by commercial activities in the rural area. The commercial loads comprise primary school, primary health centre and rural enterprises. Two-third of the rural enterprises engages in retail trade and remaining in wide range of services. Common rural enterprises are grocery shops and shops selling fast moving goods like ready-made items, hardware, sweets and snacks. Service based enterprises include flourmills, beauty parlours, tailoring, photo studio, welding machine, mobile repair, cybercafé etc. Commercial loads must be met to ensure productivity of village. Therefore, we have considered residential and commercial loads as primary loads. The load details considered for simulation are given in Tables 2 and 3.

Agricultural load includes water pumping and electric grass cutting machines. We have divided the village load into two important categories: Primary and Deferrable Loads. Primary load includes domestic load and commercial load. It has dedicated user-specified operating reserve, which responds instantly to fluctuations in electric load or power output. Deferrable load includes agriculture load, which can be met anytime within a certain time interval. Nearly 35% of the households have water-pumping system for irrigation. The average deferred load of 750 kWh/day has a storage capacity designed of 1850 kWh. Storage inherent to these loads provides flexibility in serving them. In case of excess electricity, the surplus serves the deferrable load rather than being wasted.

2.3. Microgrid configuration and planning

The optimization and sensitivity analysis of the HRES system is difficult and complicated because of many stochastic factors like the RE electricity output and load demand, the uncertainty of key parameters (such as fuel prices) make the design further complex. In this work authors have designed the RE system with HOMER Pro. HOMER is power system simulation software, which is developed by the National Renewable Energy Laboratory (NREL) of the United States. Hybrid Optimization Model for Electric Renewables (HOMER) is computer-aided tool designed by HOMER Energy LLC. The HOMER Pro is the global standard micro-grid software for optimization of micro-grid design in several sectors like village power, military bases, island utilities and grid-connected campuses [32]. Besides providing sensitivity analysis, this microgrid software simulates energy systems, configures optimized system by cost [32]. It simulates the operation of an energy system for entire lifetime, in time steps ranging from one minute to one hour. HOMER Pro possess two optimization algorithms, one utilizes original grid search algorithm to simulate all feasible system configurations as defined by the user search space, while the other utilizes the HOMER Optimizer which uses a proprietary derivative-free algorithm for searching the least-costly system. The microgrid configuration used in the work undertaken is shown in Figure 2.
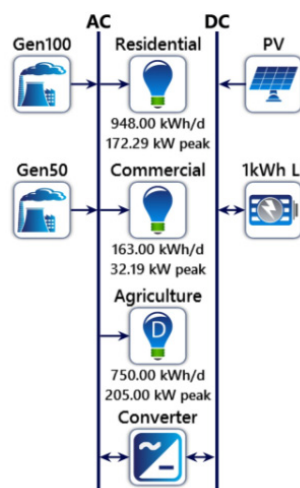
Figure 2. Microgrid configuration.

Microgrids comprise on-site distributed energy generation and distribution systems, and they employ renewable energy sources and ESS to meet the energy needs with more reliability and less carbon footprint. Planning and management of microgrids involve multi-scale decision-making, as the system should consider hourly dispatch, daily unit commitment and yearly sizing as incremental load growth over years is observed. Efficient formulations and solution algorithms encompassing all multi-scale decisions are lacking in the existing literature [33]. Further, the dynamic nature and high uncertainty of different components involved in microgrid add to the factors that limit efficient and reliable operation of microgrid. This necessitates two-stage planning, one for day-ahead unit commitment and dispatch decisions, and the other which evolve at a daily timescale. The day-ahead operation model should be integrated with values like state of commitment, battery state at the end of day and daily evolving exogenous information. In addition to this, future operating costs should be captured and optimal sizing of various components of microgrid should be determined based on some optimization function with multiple objectives like minimization of cost and emissions, and maximization of reliability.

2.4. System controller

To accomplish above mentioned microgrid planning and management goals, HOMER possess different system controllers, each with unique algorithm provide different option to users to simulate and optimize the models. In the undertaken work, we have considered two energy management strategies namely Load Following (LF) and Cycle Charging (CC). In practical cases, we accomplish implementation of these dispatch strategies by employing a suitable controller, such as PLC, microcontroller, FPGA, etc. The control strategy becomes complex when generators are included in the microgrid, as it becomes important to know in case of renewable power deficit how to supply power to the load i.e., either from batteries or from generator. In this context, two types of load dispatch strategy are explained.

2.4.1. Load following

In case of renewable power deficit, generator produces only enough power to meet the primary load demand, so generator run below rated capacity when needed. Generators do not meet lower-priority objectives such as charging the battery bank or serving the deferrable load. Load following tends to be optimal in systems with a lot of renewable power. Under the LF strategy, the systems controllable power sources are dispatched to serve the primary load at the least total cost each time step, while satisfying the operating reserve requirement. Figure 3 illustrates the operation sequence of the LF dispatch strategy for the considered HRES system.
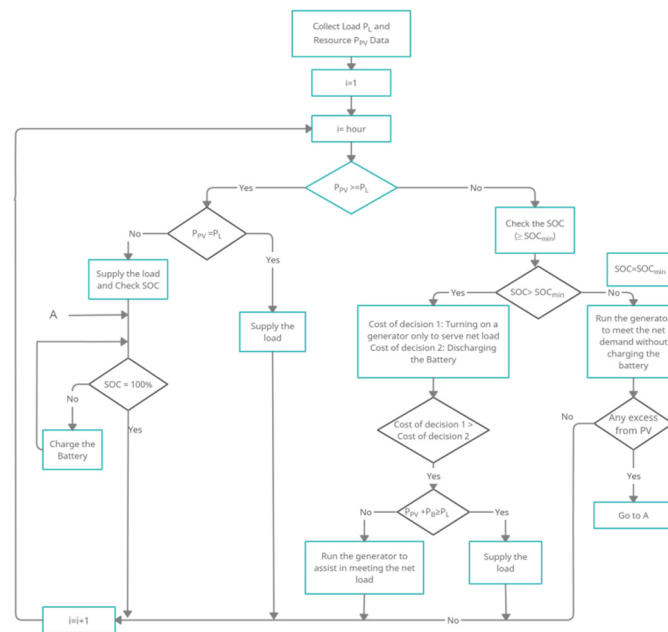
Figure 3. Flowchart of LF dispatch strategy for the PV/Diesel/Battery system.

2.4.2. Cycle charging

The operating strategy is like that of LF dispatch. However, the differing aspect is generator switching on. Here, whenever a generator must operate; it operates at full rated capacity with surplus power going to charge the battery bank, unlike LF strategy where generator runs below rated capacity. Surplus electrical production goes toward the lower-priority objectives in order of decreasing priority, like serving the deferrable load and charging the battery bank. CC tends to be optimal in systems with less renewable power. Figure 4 shows the flow of operation in the CC dispatch strategy for the considered HRES system.
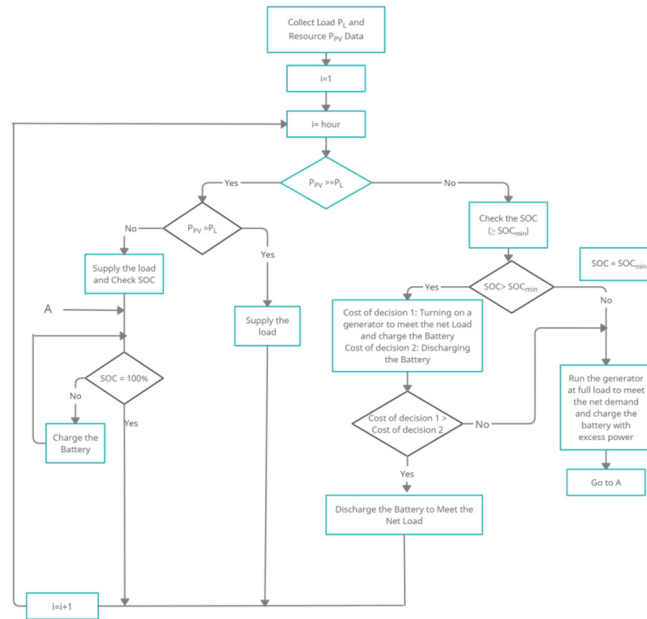
Figure 4. Flowchart of CC dispatch strategy for the PV/Diesel/Battery system.

2.5. Multi-year module of HOMER Pro

Multi-year module allows modelling the critical parametric changes of degradation of various resources and growth of several deciding factors that incurs during project lifetime. These factors include PV degradation, increase in primary and deferrable load demand, fuel cost, system fixed O&M cost etc. as shown in Figure 5. Simulation results and changes in various parameters can be viewed on yearly basis over project lifetime by using the multi-year plot as this module adds new features to results as well.

Figure 5. Multi-year inputs.

3. Details of technical and financial parameters used for analysis

Technical key parameters include load growth assumptions and project lifetime, which are crucial for precision and practicality of system design. Financial key parameters include inflation rates and nominal discount factor and cost associated with various elements of the microgrid.

3.1. Load growth assumptions

In power system, electricity demand forecasts are the basis of planning of generation capacity, transmission and Distribution (T&D) infrastructure. Besides, the governments' policies on '24/7 Power for All', energy efficiency, electricity market reforms, 'Make in India' and electric mobility are instrumental in influencing the future demand. In India, Central Electricity Authority's (CEA) carries out Electricity Power Survey (EPS). The recent 19th EPS reports electric consumption of 1300 BU (Billion Units) in the year 2021–2022 and projects an increment to 1743 BU by the year 2026–2027, with peak demand increasing from 226 GW to 299 GW in these years, considering 6.32% Compound Annual Growth Rate (CAGR) [34].

Electricity demand depends on numerous variables; some variables even consider deep uncertainty of future like Gross Domestic Product (GDP). GDP growth projections vary from 7–8% (as projected by governmental sources and IMF) to 5.5–6.5% as projected by few banks, research institutions and development organisation still the year 2030 [35]. GDP projections have different implications on economic activities and energy intensities. So, it becomes important to understand possible scenarios of electricity demand for planning distributed generations for the future. Application wise electricity demand from various sectors like residential, commercial, industry and agriculture (as categorised by the CEA), is considered for the load growth assumptions in the proposed work [36]. Expected new loads from new households under the PMAY (affordable housing programme) [37], electric cooking and electric vehicles are also incorporated while forecasting the demand. The two extreme scenarios of 5.4% CAGR and 7.4% CAGR are considered. The report suggests that the electricity demand may rise based on per capita income growth, ownership of appliances, energy efficiency, and number of households electrified. We have considered load growth assumptions based on 7% GDP and mid energy efficiency scenario. Hence, we have considered growth of 5.9% in domestic, 3.4% in agriculture and 7.5% in commercial for the proposed work.

3.2. Project lifetime

We have considered project lifetime as 15 years as the load growth assumptions consider 15 years' horizon. Load growth assumptions will not remain valid beyond 15 years of project lifetime. Further longer project lifetime has several issues of technical and economic aspects while planning a microgrid, such as, renewable energy technologies efficiency decreases over time and operation and maintenance cost fluctuations.

3.3. Inflation rates and nominal discount factor

As per inflation data of India [38], we have considered inflation rates of 5.71% per annum over project lifetime. As per CERC [29], we have considered 10.7% discount factor for renewable energy technologies.

3.4. Cost associated with various elements of microgrid

Various elements of proposed microgrid include solar photovoltaic, diesel generators, lithium-ion battery and bidirectional converter. We have discussed the fixed and variable costs of these elements in detail. We have considered fixed tracking type solar PV Panel with benchmark capital cost as specified by CERC for the work as INR 44,600/kW and O&M cost as INR 700/kW with 13% efficiency and 80% de-rating factor [29]. The solar PV capital cost includes module cost, mounting structures, civil with general works as well as power conditioning unit. We have considered two diesel generators rated at 100 kW and 50 kW for the work undertaken with capital cost of INR 600,000 and INR 320,000 and O&M costs of INR 140/op.hour and INR 110/op.hour respectively. Addition of an energy storage system (ESS) aids in maximizing the contribution of renewable, increasing PV penetration and allowing diesel-off operation and thus enabling fuel savings. We have considered several 1 kWh Li-ion batteries with 90% roundtrip efficiency and 6 V nominal voltage for the microgrid design. The capital cost of 1kWh Li-ion battery is INR 9,950 and the replacement cost is INR 4,850. We have considered a bi-directional converter for the work with capital cost of INR 10,000, for which O&M cost is zero, as converters available in market are lifetime maintenance free.

4. Simulation results and discussions

The proposed HRES is designed for multiyear load growth considering two dispatch strategies namely load following and cycle charging using HOMER Pro software [39]. In this section, we have compared the two dispatch strategies results with respect to various parameters like net present cost and cost of energy, total electricity generated, renewable penetration and average state of charge of the battery employed. Further, robustness check is analysed in detail. We have compared the proposed design with only diesel system, in terms of cost, carbon footprint and its associated social cost.

### 4.1. Technical results of the proposed system

All possible configurations that can meet the load demand by available energy resources of the proposed system are simulated. In this process, we discard the infeasible configurations. We rank the results obtained from simulation based on total Net Present Cost (NPC) and accordingly the optimal design is the feasible system configuration with least NPC. The optimal size of different components and the cost of microgrid for the considered load demand under two energy management strategies, that is load following (LF) and cycle charging (CC) strategy, as obtained from simulation is given in Table 4. It is observed that CC strategy has feasible solution with lesser NPC when compared to LF

strategy. NPC is comprised of capital cost, operating cost, replacement cost, salvage value and resource cost.

Table 4. Sizes of components and system cost comparison in CC and LF dispatch strategy.

| PV (kW)	Gen100 (kW)	Gen50 (kW)	1 kWh Li-ion	Dispatch strategy	Cost/NPC (INR)	Cost of energy (INR/kWh)	Cost of energy (USD/kWh)
1000	100	50	4000	CC	101 M	10.15	0.14
1400	100	50	6000	LF	173 M	17.30	0.23

The average electrical energy needed to serve the load demand increases from 678,906 kWh in the first year to 1370736.68 kWh in the final year of the project. Both LF and CC strategy meets the load demand without any capacity shortage with yearly increasing electrical load throughout project's lifetime. Authors have presented critical multiyear results like total load served (consumption) and excess electricity produced for both the dispatch strategies in Figure 6. We observe that excess electricity is much higher in LF strategy when compared to CC strategy. We observe that total electrical production i.e. sums of total consumption and excess electricity, in LF strategy is 2,459,117 kWh/year, which is much higher when compared to 1,654,707 kWh/year in CC strategy. Demand being the same for both dispatch strategies, increased production in LF strategy leads to higher excess electricity. The excess electric energy in the CC strategy for the first year is 58.9% (975,801.71 kWh/year) which reduces to 25.4% (420,777.69 kWh/year) for the final year, whereas the excess electric energy in the LF strategy is 72.3% (1,780,210.974 kWh/year) in the first year, which declines to 38.5% (947,541.31 kWh/year) for the final year of the project. Higher excess electricity in LF strategy is due to employment of a greater number of PV panels and correspondingly higher energy storage.
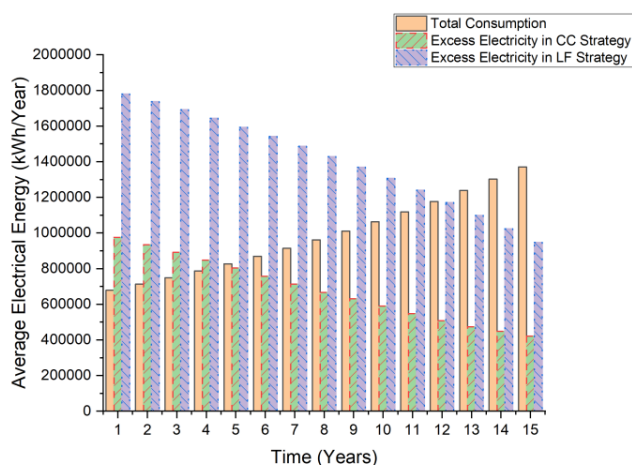
Figure 6. Total consumption and excess electricity generation in CC and LF strategy on yearly basis.

The battery parameter profile depicting autonomy vs. its output energy for both CC and LF dispatch strategy is illustrated in Figure 7. We observe that as load demand increases over the years the energy output from battery also increases in both strategies. Similarly, the autonomy hours decrease

in both the dispatch strategies. In CC strategy, the output energy increases from 228,550.96 kWh/year from start of project to 402,243.44 kWh/year in the final year, whereas in LF strategy average energy output is 194,903.68 kWh/year in 1st year, which increases to 434,047.89 kWh/year in 15th year, which can be observed in Figure 7(a). Autonomy hours in CC strategy are 41.26 in the first year and reduce to 20.41 in 15th year, while battery autonomy reduces from 53.39 hours to 30.62 hours over the years in LF strategy, as seen in Figure 7(b). This implies that in the two dispatch strategies, battery is less utilized in LF strategy consequently battery state of charge (SOC) remains comparatively higher in LF technique.
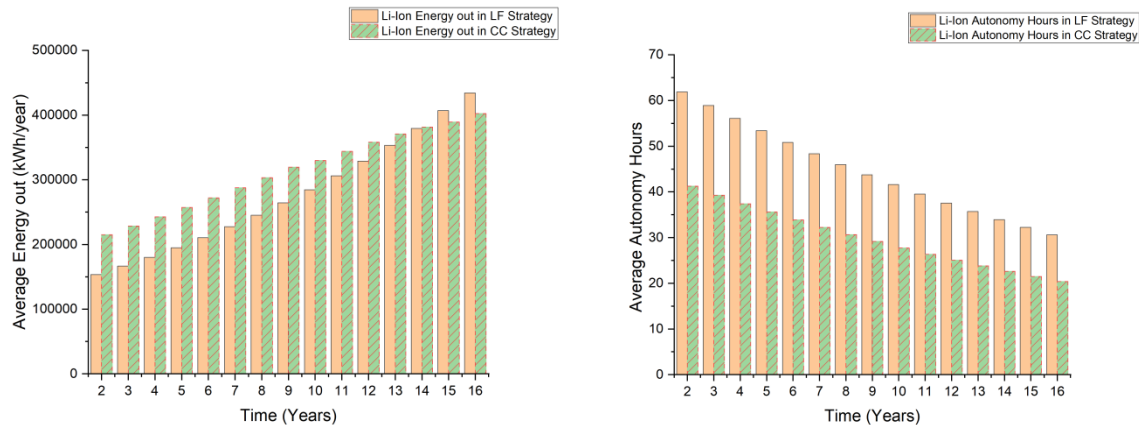

a. Average energy out of battery   b. Average autonomy hours

Figure 7. Comparison of battery parameter profile for CC and LF dispatch strategy.

HOMER utilizes abstract models of battery, namely Kinetic Battery Model (KiBaM) which is very simple yet practical. These models maintain the dynamics of the battery and are normally used in commercial software for simulation owing to its speed. This forms effective model for simulation of lithium-ion and other chemistries, and it can emulate state of charge (SOC) fluctuations using only two variables namely available capacity and total capacity.

Month wise average SOC profile of battery for CC and LF Strategy over the project life (15 years = 180 months) respectively is shown in Figure 8(a). We observe dip in the average SOC in the monsoon season of all the years, which is characterised by cloudy days. Authors observe that variation in average SOC is much higher in CC strategy compared to LF strategy. Further SOC variation increases with the life of the project as the load demand increases during later years of operation. We observe from monthly averages of SOC variations data that the average SOC during rainy season is approximately 63.5% in CC strategy whereas its 73.25% in LF strategy, during the 15th year of the project. The results suggest that the system can continue to serve the load demand after project lifetime as well. Comparison of average monthly SOC in both dispatch strategies over the entire lifetime of project reveals that average SOC in CC strategy is less than that of LF strategy throughout the project. Hence, authors have inferred that battery is used extensively in CC strategy whereas in LF strategy there is less battery throughput and more headroom for renewable with greater number of PV panels utilized in LF strategy. In Figure 8(b) illustrates monthly averages of

renewable penetration over the project life in CC and LF strategies. We observe dips in the renewable penetration during rainy season.
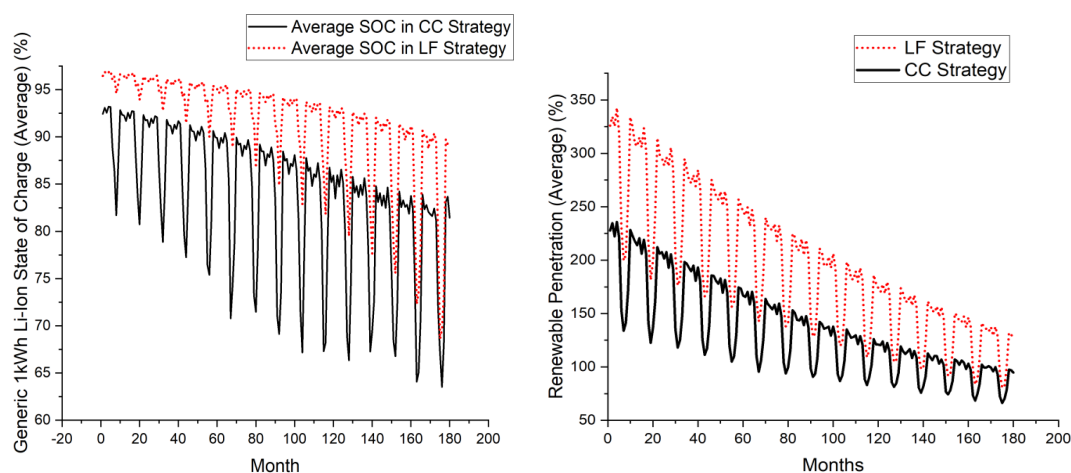

a. Average SOC profile   b. Average renewable penetration

Figure 8. Comparison of monthly average of (a.) Battery SOC profile and (b.) Renewable penetration over the project Life in CC and LF strategy.
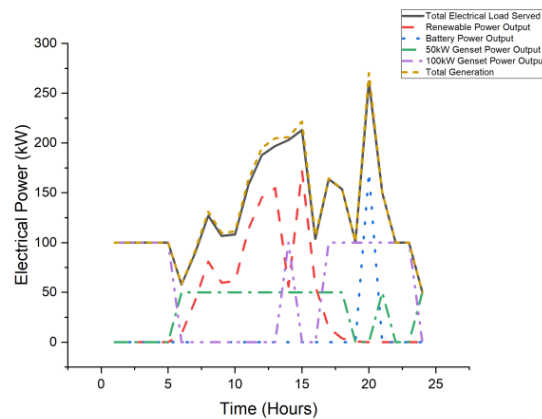
4.2. Robustness checks

Authors have simulated the project from year 2007 to 2021. We have considered First Year Profile because the load is less during first year. Total load served for the first year is 678,906 kWh and this increases to 1,370,736.68 kWh during 15th year of the project. Minimum renewable power output is present in the rainy season, in the month of July and August, which is characterised by cloudy days. For other months, we observe that the renewable power is in excess, and the renewable penetration is very high. In CC strategy PV mean output is low (approximately 190 kW) when compared to the PV output in LF strategy (approximately 270 kW). In CC Strategy, we observe large variation of battery SOC during monsoon even during first year, which signifies extensive use of batteries. While in LF strategy, where PV sizing is greater, we find that renewable energy suffices in monsoon season during first year and not much variation is seen in SOC of battery as well. While during the 15th year of operation for CC and LF dispatch strategies, higher renewable energy during summer is in excess for the increased load demand in LF strategy while in CC strategy there is significant usage of diesel generator. In the cloudy days of monsoon, the demand is met by battery storage and it can be observed battery SOC dropping considerably in both dispatch techniques. In CC strategy battery storage is seen to be used extensively throughout the year. In LF strategy, the energy storage is used substantially during monsoon.
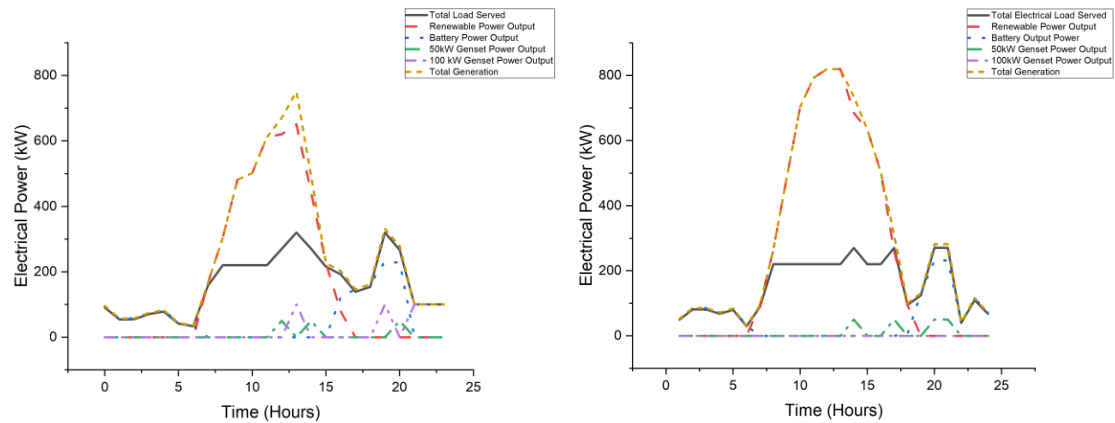
a. Electrical profile of month of January   b.   Electrical profile of month of May

c.   Electrical profile of month of July

Figure 9. Robustness check in various electrical profiles.

We investigate the technical robustness of the optimal system, that whether it can provide electricity consistently during the 15th year of the project i.e., when the load demand is highest. Figure 9a,b,c present various electrical profiles during a day for the months of January, May and July respectively. These selected months characterize extreme weather conditions, resource availability and diversity in load profiles. Figure 9 illustrates that the total generation curve is always above the load demand curve indicating technical robustness.

4.3. Economic results of proposed system and existing system

Presently, for reliable power, the rural Indian enterprises heavily rely on diesel generators and for all productive usage diesel generators are being utilized [26]. Therefore, for comparing the existing system with the proposed system, we have simulated only diesel system in HOMER Pro with same multiyear inputs of load growth. We included several diesel generators sizes in the search

space and achieved minimum cost of only diesel system for the configuration as presented in Table 5. The table presents the summary of various cost components involved in the most optimal designs of the proposed system and the existing system catering incremental loading over years for both CC and LF strategy. The differences in cost are solely based on the HOMER optimizer's calculation of optimal component sizes and prices. In the proposed system, initial capital cost and operating cost are obtained as INR 87.5 M and INR 1.30 M/year respectively in case of CC strategy, while these costs are INR 124 M and INR 4.63 M/year respectively in LF strategy. While in the existing diesel system, initial capital cost and operating cost are INR 12.1 M and INR 31.8 M/year respectively in CC strategy, and INR 11.8 M and INR 39.7 M/year respectively in LF strategy. Huge operating cost in the existing system disapproves its sustainability.

Considering the results of the optimal solution for both proposed and existing system, CC strategy of the proposed system is clear winner in terms of all valid parameters. Therefore, proposed system with CC strategy would be excellent choice owing to low lost (LCOE INR 10.15) and significant renewable penetration (94.4%) along with some excess power as well which can serve the system beyond project lifetime as well. Further, we found the COE for existing system catering incremental loading to be INR 34.86 for CC strategy and consumption of fuel/year was huge as shown in Table 5.

Table 5. Various cost components of the most optimal designs of CC and LF strategy in proposed and existing system.

System	Dispatch algorithm	Initial capital (Millions INR)	Operating cost (Millions INR/year)	Net present cost (Millions INR)	Total Fuel (L/year)	Renewable fraction (%)	Levelized cost of energy (INR/kWh)
Proposed system	CC	87.5	1.30	101	19,516	94.4	10.15
Proposed system	LF	124	4.63	173	44,781	88.2	17.30
Existing diesel system	CC	12.1	31.8	348	321,728	0	34.86
Existing diesel system	LF	11.8	39.7	432	361,075	0	43.30

4.4. Pollutant emissions of the proposed microgrid and the existing system

Authors have compared results of diesel generator operation and pollutant emissions for the proposed system and existing system. Average fuel consumption for the proposed system is 19,516 L/year and 44,781 L/year for CC and LF dispatch strategy respectively. While the average fuel consumption is 321,728 L/year and 360,075 L/year for the CC and LF strategy respectively for the existing diesel system. Enormous fuel consumption in only diesel system leads to massive carbon footprint of 841,617.6 kg/year, while carbon emission in the proposed system is 51,066 kg/year. Pollutant emission is significantly higher in only diesel system.

5. Conclusions

The existing electrical systems of rural India, which are heavily dependent on diesel generators for any productive usage, are not sustainable systems in terms of both economics and environment. Rural India demands the shift to environment friendly renewable energy systems. Therefore, we have undertaken the Hybrid Renewable Energy System for this work. In the proposed system, research gaps based on the designs of microgrids and feasibility evaluation that are present in the existing literature are outlined and addressed. Near actual load data of rural India are collected from survey of the consumer demand behaviour of more than 10,000 households. Authors have employed Multiyear module of HOMER Pro for implementing incremental loading over years. Levelized Cost of Energy amount to INR 10.15/kWh and INR 17.3/kWh for CC and LF strategy respectively in the proposed system that serve incremental loading over years. These LCOEs are significantly less than the existing Diesel System with the cost of INR 34.86/kWh and INR 43.3 in CC and LF strategy respectively.

Further, renewable penetration of the proposed system with CC and LF strategy is 94.4% and 88.2% respectively. We observed CC dispatch strategy to be more optimal when compared to LF with lesser NPC, LCOE and carbon footprint. Hence, for the considered incremental loading, CC strategy is appropriate for the microgrid design. The excess electrical generation and the average SOC in CC strategy is 25.4% and 63.5% respectively by the 15th years, which suggest that we can use the system beyond project lifetime as well. The study identifies the significance of consideration of incremental load growth over years in developing countries and appropriate dispatch strategy as well, to avoid any financial and technical errors. Hence a pragmatic microgrid is designed which could serve the rural India with reliable power. In future works, the design scenarios can be extended and employment of second life EV batteries for cost reduction can be considered.

Conflict of interest

The authors declare that there are no conflicts of interest related to this study.

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